Solar System/Planet Formation

Gas Clouds to Stars/Planets

Planet Migration

Satellite Formation
Formation of the Solar System

**STEPS:**

1. **CLOUD COLLAPSE**
2. **ROTATING DISK**

**EVIDENCE:**

1. Young stars seen in collapsing gas clouds
2. Planets orbit in the same direction and same plane
3. Sun and planets rotate in the same direction
4. Disks seen around other stars
The most abundant raw materials:

1. H, He gases
2. “ices” (hydrogen compounds)
3. rock and metal
• Tiny ‘dirt’ particles formed from condensed rock/metal

• Tiny ice crystals condensed from hydrogen compounds like water… but ONLY far from Sun due to thermal gradient
Examples of Condensation

Inner solar system:

↔ rocky, metallic dust condensed together into small objects

meteorite cut-away:
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- Jovian planets, icy moons, comets found farther away
Accretion

“Sticky” collisions of dust and snowflakes make bigger particles:

Planetesimals (like asteroids and comets: several km across) slowly form, until gravity is strong enough to help pull them together:

Larger protoplanets slowly form from these collisions:
Elastic or inelastic collisions?

Coefficient of restitution = $\frac{V_{\text{rebound}}}{V_{\text{impact}}}$

(accretion only proceeds when $V_{\text{rebound}} < V_{\text{escape}}$)

Accretion

- many small objects collected into just a few large ones
- collisions become less frequent as more material becomes ‘stuck’ together
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- Many meteorites are made of smaller bits
- Heavy cratering on oldest planet surfaces
- Asteroids, comets are “leftovers”
Cores of jovian planets are large enough ($\geq \sim 10 \ M_{\text{Earth}}$) that their gravity captures and holds gas (hydrogen and helium).

→ Uranus and Neptune may have reached this core size too late to capture substantial gas before it was blown out of the solar system.
HD 141569 Circumstellar Disk
Hubble Space Telescope - ACS HRC Coronagraph
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- Jupiter, Saturn are mostly hydrogen and helium
Gas is eventually captured or pushed out by wind from the star, but dust and planetesimals remain. 

→ Late collisions form “debris disks”
Debris disks → infrared excesses

![Graph showing infrared emission from GJ 803]
The randomness of it all…

Physical properties also affected by randomness of late accretion
- Rotation rates/obliquities
- Bulk composition (Mercury)
- Surface topography (Mars)

Giant planet sizes/orbits also influenced by random chance…
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Close-in Giant Exoplanets → Migration
Close-in Giant Exoplanets \(\rightarrow\) Migration

Kepler Candidates as of February 1, 2011

- Size Relative to Earth
- Orbital Period in days
Inward Planet Migration

• Probably through angular momentum exchange with disk gas
  - Type II: planet orbits in disk gap
  - Type I: no gap

• Stopping migration before planets merge with the star may require concurrent nebula dissipation

Papaloizou & Terquem (2005)
Inward Planet Migration

1.5\(M_{\text{Jup}}\) planet in 0.02\(M_{\odot}\) disk (MMSN):
~100 orbits ending with simulated gas dispersal

http://planets.utsc.utoronto.ca/~pawel/planets/movies.html
All planets formed at <20 AU (high density, short orbital periods).
Outermost planet (Uranus?!) interacted with KB planetesimals, typically “passing” them inwards to interact with other planets.
Interactions with Jupiter cause ejection to Oort cloud or beyond.
Reflex planet migrations cause Jupiter and Saturn to cross 2:1 resonance → mayhem!
- *Uranus and Neptune move way out, switch places?*
- *Planetesimals scattered into inner solar system (LHB)*
Outward Planet Migration: Nice Model

![Graph showing migration of planets with time (yr) on the x-axis and various parameters (a, q, Q) on the y-axis. The graph highlights the 1:2 MMR (mean motion resonance) and various other markers indicating specific parameters and time scales.](image-url)
Problem: Terrestrial planet destabilization

Solution: 5th planet!?

Nesvorný (2011)
Ejection of a 5th giant planet?

Nesvorný (2011)
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Satellite Formation

Gaseous Pillars · M16

PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA
Satellite Formation Mechanisms

- Circumplanetary accretion disks ("regular satellites")
- Capture ("irregular satellites")
- Giant impacts
Formation of Regular Satellites

- Regular Satellites:
  - $M_s \sim 10^{-4} M_p$
  - $a_s < \sim 20-30R_p$
  - $e, \ i \approx 0$

- Form in “subnebula” of ~solar composition?
Capture of Irregular Satellites

- Irregular Satellites: small, distant, eccentric and/or inclined (often retrograde)
- Capture due to 3-body interactions (collisions or scattering) most likely, probably early

Jewitt & Haghighipour (2007)
The Oddballs: Formed by Impact?

- Earth’s Moon (~10^{-2}M_{Earth}) (Canup, 2004)
- Charon (~10^{-1}M_{Pluto}) (Canup, 2005)

For our Moon, this explains:
- Age (~4.4 – 4.53 Ga)
- Low volatile content
- Low bulk density (minimal iron core)
- Similar oxygen isotope ratios to Earth
- Early proximity and fast rotation of Earth